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Before the Federal Communications Commission
Washington DC 20554

In the Matter of
Advanced Television Systems
and Their Impact upon the
Existing Television Broadcast Service

MM Docket 87-268
Fourth Further Notice of Proposed Rule Making and Third Notice of Inquiry
9 August 1995

Comments of

William F. Schreiber
Senior Lecturer, Professor of Electrical Engineering, Emeritus
Research Laboratory of Electronics
Massachusetts Institute of Technology
17 October 1995

The opinions in these comments are those of the author only.

36-545 MIT, Cambridge, Mass. 02139 617 253 2579 wfs@image.mit.edu

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Executive Summary

These comments deal, for the most part, with the efficient use of spectrum in digital TV broadcasting, a matter on which the Commission and its individual members have placed a great deal of emphasis. When the rules for NTSC broadcasting were adopted, spectrum was not thought to be in short supply. With the rapid growth of new wireless applications such as cellular telephone service and PCS, this is no longer the case. Spectrum is very valuable, and is about to become very scarce.

We define spectrum efficiency (SE) as the number of different programs of a given technical quality that can be made available to each viewer per unit of total allocated spectrum. SE depends on both (1) the required bandwidth per program and on (2) the number of programs that can be transmitted without interference in each locality. The Grand Alliance system has markedly improved the first factor, which depends mostly on source coding, but has done little about the second factor. The second factor depends on channel coding and on regulations of the Commission as to the location and frequency assignment of stations and as to the performance of receivers.

At present, no more than 20 channels are usable in any city out of the 67 that are allocated. Going to a totally new system presents the rare opportunity to do much better. With appropriate technology and regulation, only 20 channels would have to be allocated to provide 20 different programs, once the transition to the new system were complete. The long-run construction and operation cost of such an approach would not be higher than the cost to implement the Grand Alliance system, and might be less. The final result would return a great deal of currently allocated spectrum to the Commission for reassignment, greatly alleviating the projected spectrum shortage.

The factor 20/67 is so low because stations on the same channel must be 150 miles apart, because adjacent channels cannot be used in the same city, and because of the existence of certain "taboos" that are now obsolete but must be preserved in NTSC to permit existing receivers to operate properly. The adjacent-channel problem can be eliminated by requiring co-location of new transmitters in the same city. The co-channel problem can be eliminated by the use of single-frequency networks, a kind of cellular broadcasting system. The latter requires the adoption of a channel coding and modulation scheme with strong resistance to the effects of high-level ghosts. The other taboos can be eliminated by requiring appropriate receiver performance, which no longer would be particularly costly.

The SFN approach involves a cellular network of low-power transmitters rather than a single high-power centrally located transmitter as used at present. The service area of each station is determined by the location of cellular transmitters rather than by the total radiated power. All receivers in the service area get a good signal without the use of high-performance directional antennas.

SFNs can be implemented on a city-by-city and channel-by-channel basis. In some rural locations, they might never be needed. Their operating cost would be much lower than that of the current system, since the total emitted power would be much less. If the practice of using common cellular sites for all radio broadcasting were to develop, a great deal of money could be saved by the industry, and TV broadcasters could finally get out of the business of operating the physical broadcasting equipment.

A second set of issues that can be dealt with on the occasion of going to a new system relates to the fact that the Grand Alliance approach potentially provides identical-quality images to all receivers in the reception area as long as they receive a signal above a certain threshold. This means that all receivers must have a full decoder, even if they have a nine-inch screen and are used exclusively for watching the news while eating and cooking. It also means that most receivers utilize only a fraction of their data-reception capacity, thus reducing their potential image quality and creating unnecessary interference to other services. In the single-transmitter scheme, the multiresolution approach raises SE by improving quality in high-signal locations and extending coverage in low-signal locations. It also supports the provision of lower-cost receivers for less-demanding applications. In the SFN scheme, there is no effect on SE, but there is still support for lower-cost receivers.

1. Introduction

The Notice as well as comments from the individual Commissioners indicate that efficient use of the broadcast spectrum will be a major consideration in future decisions. This position is entirely reasonable in view of the rapid increase in wireless applications, both existing and proposed. The astonishing growth of cellular telephone service is an example. In this section, we present the background for modern views of the importance of spectrum efficiency, and some comments about the roles of source and channel coding.

1.1 Earlier attitudes towards spectrum efficiency.

Spectrum was not always thought to be in short supply, in part because technology was continuously extending the usable spectrum toward higher frequencies. In the absence of an actual shortage, early decisions about how much spectrum might be allocated for a particular service were governed by equipment considerations, and not by spectrum usage. This was especially true for decisions about television broadcasting, which now occupies 67 6-MHz channels -- about half of the entire spectrum that might economically be used for consumer services.

In retrospect, it appears that many of the features of today's spectrum allocation for television were chosen primarily to reduce the cost of building transmission facilities and to minimize the cost of TV receivers. For example, there was never any Commission requirement to locate all transmitters in each city in the same place (co-location), as a result of which adjacent channels cannot be used in the same city. There was no selectivity requirement imposed on receivers, which has made many channels unusable (taboo), particularly in the UHF. Finally, the normal transmission scheme makes use of a single centrally located transmitter for each station, giving rise to highly nonuniform electromagnetic field strength through the service area. The net result of such arrangements is that a maximum of only about 20 channels can actually be used in each large city.[1]

The most important feature of the new "digital television" system that is now proposed -- the Grand Alliance (GA) system -- is its capability of transmitting four or more standard-definition signals in a channel that, with NTSC, can transmit only one signal.[2] From the spectrum-allocation viewpoint, this amounts to a bandwidth reduction factor of 4, which is equivalent to requiring only 1.5 MHz rather than 6 MHz for one signal. As useful as this is for the efficient use of spectrum, it is just as important to raise the ratio 20/67 as it is to reduce the bandwidth required for a single signal. As we shall see below, it is pos-

[1] If an equal number of channels were to be usable over the entire country, this number would be no more than 17, and even less without some requirement on receiver performance. In the UK, where equal service is provided everywhere and similar taboos are in effect, only 4 channels are usable out of 44.

[2] The current form of the GA system does not have this capability, but there is no doubt that it can be added.

sible, with the right technology and with appropriate rulings by the Commission, eventually to be able to use every channel in every location. This is equivalent, in terms of spectrum utilization, to reducing the bandwidth of a signal by a factor of (67/20 =) 3.35, a ratio almost as large as that achieved by moving from today's NTSC system to the totally new digital system.

1.2 The role of source and channel coding in efficient spectrum usage.

To understand the options that are available for improving spectrum utilization, it is essential to keep in mind the separate but complementary roles of source and channel coding. In Fig. 1, we show the succession of steps that are used to process the video signal from the TV camera, transmit it through the terrestrial broadcast channel, and to recreate a good approximation of the signal at the input of the display device in the viewer's home.

An optical image of the scene is projected onto the sensitive surface of the camera sensing device, (tube or chip) where it is scanned in the familiar raster pattern to produce a video signal. The source coder takes the video signal from the camera or production system and produces a data stream that more or less accurately represents it. In the GA system, the data stream is digital, and the source coder reduces its data rate by a factor of about 30 compared to what it would be without compression. It does this by eliminating unnecessary information (spatial and temporal redundancy) from the video signal.[3] The channel coder takes this data stream and prepares it for transmission in the broadcast channel so that it can be received accurately in spite of channel impairments such as noise, interference, and ghosts. This requires extensive forward error correction. The transmitter raises the power of the signal and impresses it on a radio-frequency (rf) carrier for transmission.

At the receiver, the process is reversed. The rf receiver demodulates the signal and translates it to baseband. The channel decoder recreates the digital data stream produced by the source coder, one of its most important functions being bit-error reduction. The source decoder recreates a video signal much like that produced by the TV camera, in the process reinserting the redundant information that was removed by the source coder.

The steps described are necessary in any kind of transmission system, analog or digital, but the characteristics of the resulting systems are markedly different. In NTSC, which is entirely analog, image quality deteriorates continuously as the received signal becomes noisier and otherwise impaired. The quality of the reconstructed signal, given a certain degree of impairment, depends on the antenna performance as well as the design and

[3] A compression factor of about 8 is needed just to transmit digital data in the analog channel, while another factor of 4 is needed to accommodate either one high-definition image or 4 standard-definition images in one channel.

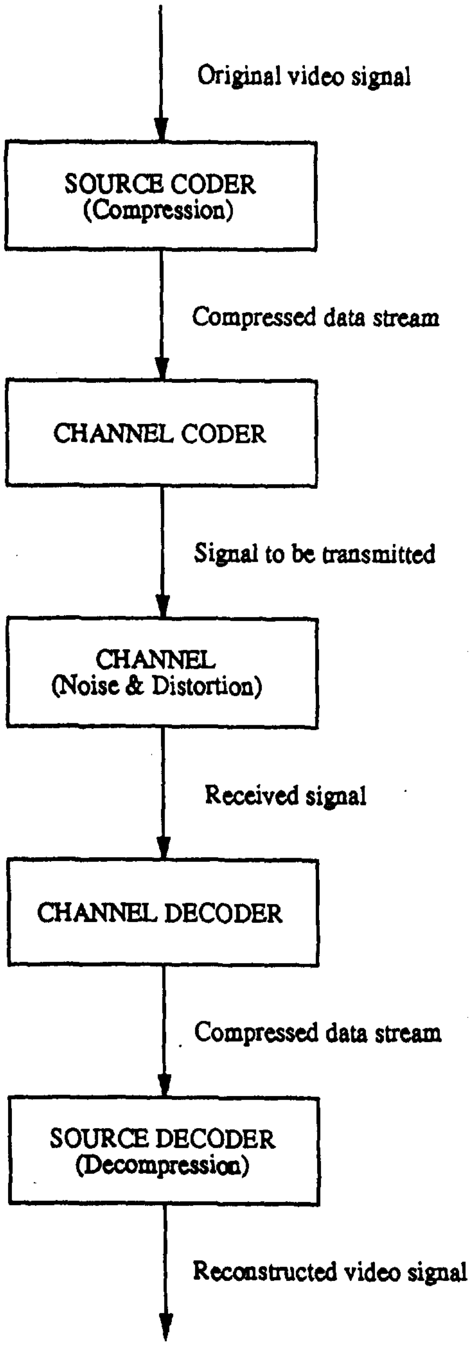

Figure 1. Source and Channel Coding

This diagram shows the steps that video information undergoes as it progresses from the output of a TV camera or TV production system to the input of a display device such as the picture tube of a home receiver. Note that the primary function of the source coder is data compression, while the primary function of the channel coder -- merely a modulator in simple analog systems -- is the preparation of the information to withstand the noise and distortion introduced by the channel.

performance of the front end of the receiver. In general, quality deteriorates smoothly with distance from the transmitter.

In fully digital systems, such as the GA system, the quality represented by the compressed data stream depends on the complexity and degree of motion in the original material, most of the time being perfectly adequate. In the absence of bit errors, no further degradation takes place in transmission. However, as noise, interference, and ghosts are introduced, errors are produced in spite of the use of powerful error-correction methods. The image quality remains constant, as set by the source coder, up to a given level of contamination, at which point the error-rate reaches a critical level. Just beyond this point, service becomes unusable. Of course, the threshold of service can be extended by using a better antenna and receiver. There is little experience with viewer reaction to this so-called "cliff effect," so that the relative effective coverage of digital and analog systems remains to be demonstrated.

2. Spectrum Efficiency

We define spectrum efficiency (SE) quantitatively as the number of different programs of a certain technical quality that can be made available to each viewer within a given allocation of spectrum for the broadcast service. We now discuss the factors that influence the spectrum efficiency actually attained, starting with a simple arrangement of transmitters and progressing to more complicated arrangements. As we shall see, some of these relate to the choice of technology, but others of great importance depend on the regulations set by the Commission that govern how the TV service is to be implemented.

2.1 Bandwidth needed for a given image and sound quality on a perfect receiver.

This is primarily a function of the source coder. There is naturally a tradeoff between quality of reception and bandwidth per program. For more than 50 years, we have assumed that the NTSC standards of 525 lines interlaced at 30 frames/sec gave a reasonable quality,[4] and the required 6 MHz a reasonable bandwidth, without examining either assumption very carefully. However, we can reach conclusions about the relative spectrum efficiency of different systems without reference to the precise quality that is to be delivered.

It is perfectly obvious that any reduction of bandwidth that does not reduce image quality must raise the SE in proportion. For many years, it was the nearly unanimous opinion in the TV industry that bandwidth compression must inevitably reduce quality. On the other hand, it was always easy to get agreement with the proposition that it might be

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[4] Actually, the image quality seen on typical home receivers has always been far below NTSC studio quality, so that many viewers think that the latter is really HDTV. This was clearly demonstrated in audience tests carried out at MIT.

possible to improve quality without requiring additional bandwidth, since several kinds of video processing equipment, such as noise reducers and edge-sharpeners, had just this effect. The fact that these two propositions were logically equivalent was usually not appreciated. It was largely the efforts of General Instrument Corp., which proposed the first all-digital system using a compression method quite similar to MPEG, that reversed overnight this long-held opinion about comporession. In any event, it is now universally assumed that MPEG-type source-coding schemes can give a bandwidth compression factor of about 4 with no loss of quality, (most of the time) and thus raise the SE by that amount. Should superior source-coding methods be developed in the future, e.g., by means of statistical multiplexing, then the SE could be raised further.

2.2 The effect on SE of the allocation of channels and the location of transmitters

In addition to the obvious effects of compression, SE is also greatly affected by the location and frequency assignment of transmitters.

2.21 *A single transmitter for each channel, co-located, in one city only.* Since all channels have the same field strength at all points, it is simple for receivers to tune to any one station without interference from the rest. All channels can thus be used. SNR generally sets the range of successful reception, although ghosts may affect the useful range, depending on the channel coder. The range may be increased without theoretical limit by increasing antenna height and effective radiated power (ERP).

2.22 *The arrangement of the previous section, but with transmitters in nearby cities.* This introduces two new restrictions. Stations on the same channel in adjacent cities interfere with each other, and a nearer station on one channel may interfere with a more distant station in an adjacent channel. There is no way around the first problem. It requires a minimum distance between stations on the same channel. This distance is about 150 miles in NTSC.[5] The exact figure depends on the signal/interference ratio (S/I) needed for a given quality of service, the ERP, and the type of receiving antennas assumed to be in use. The minimum separation requirement generally means that the same channel cannot be used in adjacent cities, which reduces the SE by a factor of 2.

The second problem is less serious, since one can always tune to the closer station on each channel, although, in the US, the two stations are unlikely to have identical programming. However, there is a much more serious adjacent-channel problem that occurs in practice.

2.23 *The arrangement of the previous section without the requirement for co-location.* In American practice, transmitting antennas are not required to be co-located. If all chan-

[5] To permit the assignment of a second channel to each current licensee for use during the period of transition to an all-HDTV service, this distance must be reduced to about 100 miles. This calls for a substantial decrease in the required signal-to-interference ratio (S/I).

nels were used in every city, it would often occur that the desired station is much further away than an undesired station in an adjacent channel. The FCC has never placed an adjacent-channel rejection requirement on receivers that would enable them to function properly under such circumstances. The "solution" is not to allow adjacent channels to be used in the same city This certainly reduces the SE, but by an amount that is not easy to determine, since the co-channel interference restriction eliminates many of the same channels that would be eliminated by the adjacent-channel restriction.

2.3 Other taboos.

In addition to the limitations on channel usage due to co- and adjacent-channel interference, there are other taboos, particularly in the UHF, that arise out of other assumed limitations on selectivity of receivers. For example, receivers that lack a tunable rf amplifier preceding the mixer cannot distinguish between signals that are above and below the local-oscillator frequency by an amount equal to the receiver intermediate frequency. These assumptions are now out of date, but there is no way to eliminate such restrictions in NTSC without making obsolete all existing receivers. On the other hand, there is no need to maintain these restrictions in a new system with new receivers utilizing today's technology.

2.4 The effect of single centralized transmitters.

Receiver SNR declines with range in typical cases as shown in Fig. 2.[6] Since the theoretical channel capacity -- the ability to deliver information -- is proportional to bandwidth times SNR in dB, this indicates that the channel capacity at the threshold of service is 4 to 5 times that at close-in points. Analog systems like NTSC make use of this added capacity to deliver pictures of higher quality. The GA system in its present state delivers the same quality everywhere, thus wasting a great deal of capacity in precisely those locations where spectrum is in highest demand. In digital systems, the provision of SNR many times higher than needed does not give better pictures, but it does cost more and does produce more interference to other services.

There are two possible ways to deal with this situation. A multiresolution system could be used that would provide higher quality close in and extended coverage, albeit at lower image quality, beyond the GA threshold of service. Multiresolution systems have the added advantage that they support the design of lower-cost receivers as well as the non-disruptive improvement of quality over time that the Commission has often requested. The second method is to make the field strength much more uniform by replacing the single-transmitter concept with a cellular arrangement of low-power transmitters all

[6] This relationship does not adhere to the inverse-square law. At close-in distances, the fact that the transmitting antenna is far above the receiving antennas makes the field strength vary more slowly with distance. At far-out locations, the signal is received nearly horizontally, and therefore decreases much more rapidly due to refraction by building and other obstacles.

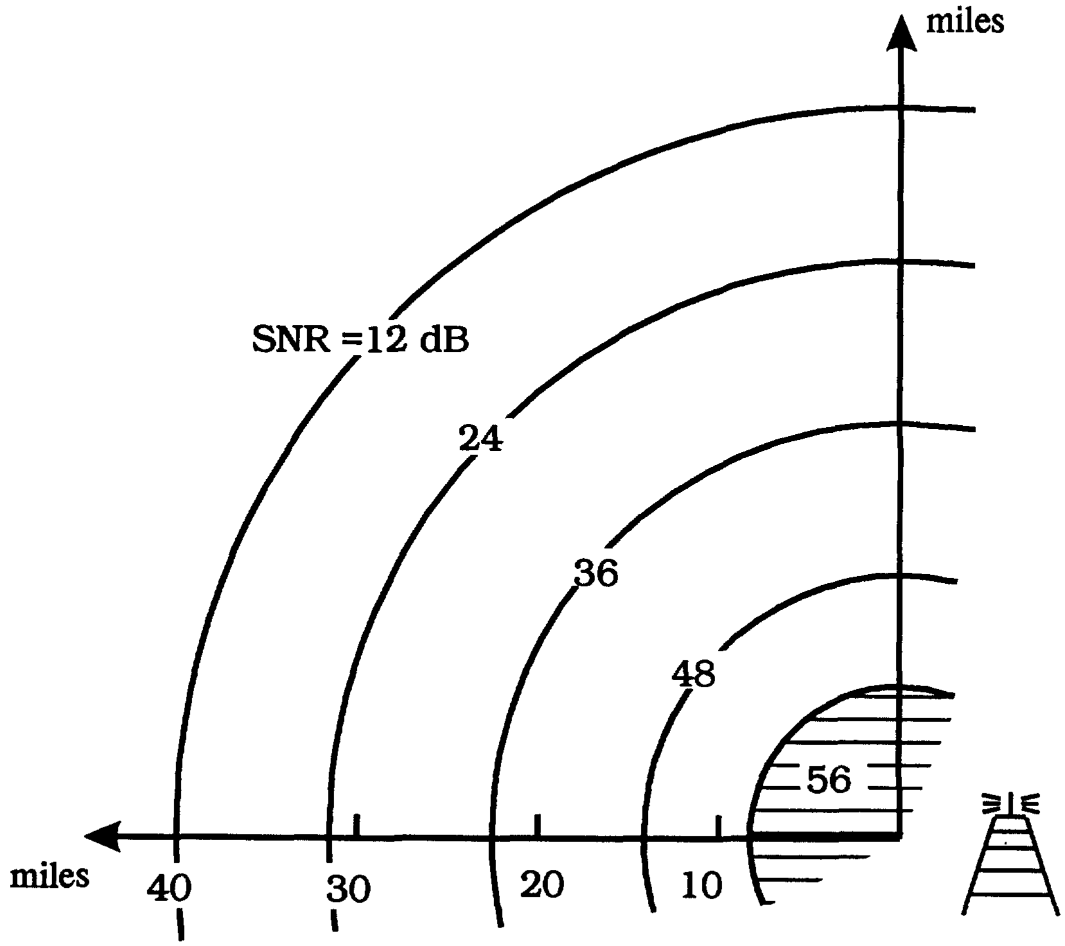

Figure 2. Variation of SNR with Range

This shows how the field strength at the receiving antenna varies with distance from the transmitter for a typical antenna installation, in this case 1200 feet high. Certain FCC planning factors are included in the diagram. Note that, except for the central area, where the SNR is fairly constant, the field strength in dB decreases almost linearly with distance. The flat central area is due mainly to the vertical antenna profile, which causes the antenna to be aimed above the receiver. The rapidly decaying field strength at long range is due to refraction of the horizontally incoming power by houses and other obstructions on the ground. If the ERP is changed by X dB, then all the SNR values change by the same amount. This shows that raising the power is a very ineffective way to increase range. It also shows that, in a single-frequency network with small cells, the required transmitter power is very low. (Data from Dr. Oded Bendov) emitting the identical signal. This scheme, called the single-frequency network (SFN), produces the highest possible spectrum efficiency and has many other advantages. It will be described in Section 4. Note that in a SFN, multiresolution does not improve SE, but it still supports lower-cost receivers.

3. Spectrum Efficiency in the Grand Alliance System

The improved SE of the GA system comes entirely from the fact that its required S/I ratio is lower than that of NTSC. (Of course, if only standard-definition programs are transmitted, the SE is raised by an additional factor of 4, perhaps even higher.) This permits stations on the same channel to be separated by only 100 miles, rather than 150 miles, as at present.

The FCC's intention to give each licensee who wants one a second channel for use during the transition period to HDTV was based on Zenith's original representation that its now-abandoned hybrid analog/digital system could be transmitted at very low power and therefore could be used in taboo channels. However, calculations and experiments with the GA all-digital system show that its required ERP is only about 12 dB lower than that of NTSC. This, together with some investigations by broadcasters on a city-by-city basis, indicate that there are many large cities in which there are simply not enough suitable channels for assignment if all licensees decide to move to HDTV. Some of this difficulty comes from adjacent-channel interference rather than co-channel interference, which was once thought to be the main limitation. Thus, the improved SE promised by the GA system is less than a factor of 2, and the amount of spectrum that will be returned to the Commission for reassignment will be considerably less than expected if the GA system is put into operation.

4. Single-Frequency Networks

We define a SFN as a cellular arrangement of transmitters, all emitting the same signal. Receivers each "see" a number of signals of different amplitudes and time displacements that are indistinguishable from ghosts. Channel-coding systems that can successfully deal with this type of signal, preferably with nondirectional antennas, produce a much more uniform SNR across the total reception area than single-transmitter systems, require much less total emitted power, and are suitable for irregularly shaped service areas on the same frequency that abut each other. Potentially, SFNs produce the highest possible SE, in that no more channels need be allocated for the entire country than the number of programs that are to be made available to each viewer.

4.1 Channel coding for SFNs.

Resistance to multipath distortion (echoes) is the primary requirement in channel coding for the SFN. Multipath produces linear distortion, which can be corrected by an appropriate equalizer (filter). In the GA system, a considerable portion of the signal-processing hardware in each receiver is devoted a time-domain equalizer to implement this function. Even then, echoes of a level that occur in a SFN generally cannot be corrected by a practical equalizer of the type used. Furthermore, this kind of correction generally results in a lower SNR, higher error rate, and smaller coverage.

Considerable attention has been given to the possible use of coded orthogonal frequency-division modulation (COFDM) as a means of making SFNs feasible. COFDM, which is the technique favored in Europe for digital terrestrial broadcasting, splits the data to be transmitted into a large number -- hundreds or even thousands -- of streams, each of which is modulated onto a different one of an equal number of closely spaced carriers within the passband of the channel. Its complexity is comparable to that of the single-carrier scheme used by the GA.

Proper comparison of COFDM and the GA single-carrier scheme is very difficult. This has been the main subject of study of my two students and myself for the past several years. An adequate discussion would be far too technical for this submission, so it is only possible to summarize our results here and to refer those interested to several papers that are attached. We have found that, by using either COFDM or a single-carrier system with appropriate interleaving (scrambling) and error correction, it is possible to have a *higher* SNR (lower error rate) in the presence of a 0-dB echo (one as large as the main signal) than with no echo at all. To do this, the single-carrier system must employ a so-called frequency-domain equalizer (not used in the GA system), which adds some complexity to the receiver. It seems to be simpler to achieve this kind of performance with COFDM, in which frequency-domain equalization is inherent. In either case, the echoes are constructive, not destructive. To some extent, it is possible to make good use of the multipath signals, rather than to suffer degradation of performance in their presence. This is shown in Fig. 3. Note that the performance *improves* with the echo power, the reverse of the situation in the GA system.

What is to be emphasized is that *much better SFN performance is achieved by either of these methods than by the GA system.* It is highly unlikely that the latter could be used with a SFN except, perhaps, with a very high-performance antenna that is properly adjusted for local reception conditions. The alternative technologies discussed in this section, on the other hand, can be used with rabbit ears or omnidirectional antennas. This capability, of course, is very useful even in the centralized-transmitter scheme.

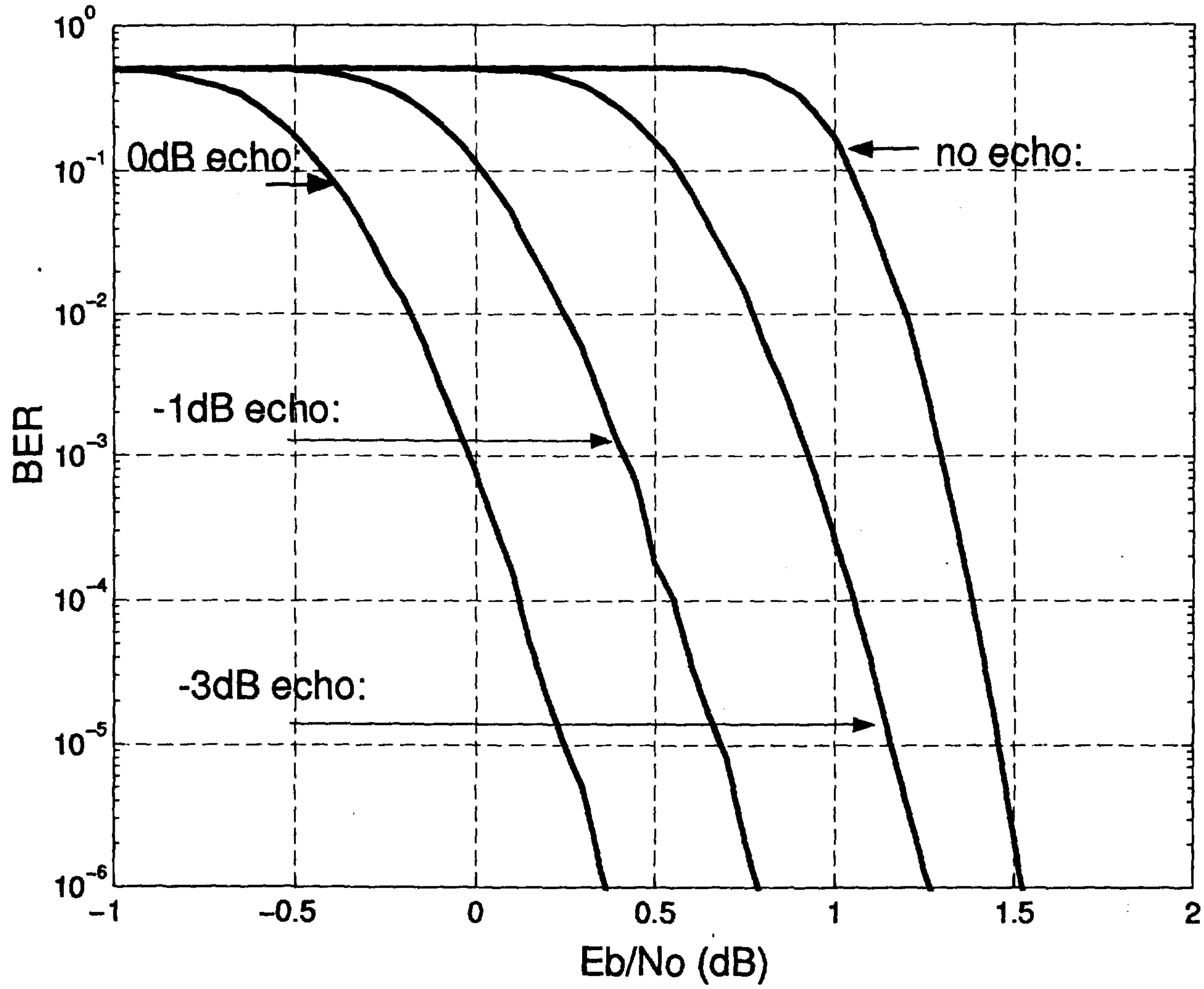

Figure 3. Variation of Bit Error Rate with Amplitude of a Single Echo

A channel coder with interleaving and forward error correction in the form of concatenated trellis and block coding can actually benefit from the presence of large echoes. This data relates to a 4-QAM system of the type discussed in the Appendix. It is not claimed that this is the best possible channel coding system for use in single-frequency networks. However, its existence demonstrates that it is indeed possible to design systems that can operate successfully in a SFN without the use of directional antennas.

4.2 Characteristics of SFNs.

The service area of a SFN is defined by the location of the cellular transmitters. This makes it easy to deal with irregular areas, such as along coastlines, and with areas that would be shaded from a central transmitter by mountains, such as in Los Angeles. In the presence of an abutting service area from another station on the same frequency, it is only in the single row of cells at the boundary between service areas -- a very small proportion of the service area -- that there would be any co-channel interference. This would be dealt with by directional antennas. Note that, in NTSC, there is usually a sizable area between co-channel stations where neither can be properly received except with very special equipment.

Were all TV transmission to be by SFNs, there would be no adjacent-channel interference, since there would be no case in which the signal from an adjacent channel were much larger than that in the desired channel. During the transition period, where a single-transmitter adjacent-channel NTSC station were located nearby, there might be interference into the NTSC signal in the neighborhood of the cellular transmitters. Generally speaking, this would occur only in areas where the NTSC signal was very low, in most cases where the reception is not protected by the license.[7] This problem can be alleviated by using rather small cells with transmitting antenna heights sufficiently higher than receiving antenna heights so as to avoid excessive signal strength. In certain cases, the full benefits of the SFN might not be available until after NTSC is taken off the air.

Small cells can be combined with a single large cell in the central area, or even a small satellite footprint. However, it is essential that the magnitude of the relative delays of the different paths that produce significant signals at the same receiver not be very large. The larger the temporal spread of the echoes (actually, the impulse response of the effective channel), the more carriers are needed. It has been suggested to use as many as 8000 carriers, which would support cells about 10 miles in diameter. While this does not increase the receiver complexity, it does increase the sensitivity to phase instability in the system carriers. Another reason for favoring small cells is to have a more uniform signal strength, which would reduce interference into adjacent NTSC channels.

The signal to be emitted must, of course, be delivered to the cellular transmitter sites. The most direct way is by radiation, perhaps on the same frequency, from a centrally located transmitter making use of a high-gain receiving antenna. Alternatively, each transmitter can pick up its signal from that broadcast at the next most inward site, again using a high-gain antenna and low-noise receiver. In some cases, all transmitters could receive their signals by satellite or by cable. It is likely that the best method would not be the same everywhere.

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[7] Of course, one would prefer not to lose coverage even where it is not protected.

4.3 Spectrum efficiency with SFNs

Given a certain bandwidth requirement for the transmitted information for a single program, no system can achieve higher SE than the SFN scheme. After NTSC is shut down, the total number of channels that must be allocated is no more than the number of programs that are to be provided to each viewer. This is because there is neither co-channel nor adjacent-channel interference. The former is eliminated by physical separation of the areas into which the signals from the various stations are delivered; the latter is eliminated since the unwanted adjacent-channel signal is never very much larger than the wanted signal. It is further assumed that the other taboos will be eliminated by regulations of the Commission.

Further comparison of the SE that can be achieved by the SFN method as compared to the single-transmitter method can be made with respect to service other than in the largest cities. The ratio 20/67 that is now achieved in the large cities is partly at the expense of service in the surrounding areas, as only 17 channels would otherwise be usable, even without the noninherent taboos, if there were a commitment to provide equal service everywhere, as in the UK. If SFNs were used in these large cities, then there would be no interference at all into transmissions elsewhere.

4.4 Implementation strategy.

Even though a cellular system would be cheaper to operate and probably cheaper to erect than a single-transmitter system, the conversion from the latter to the former does involve some expense. A number of strategies can be adopted to stretch out the expense over time and to minimize the final cost.

As long as NTSC is on the air, it will be necessary to retain the full allocation of 67 channels in order to maintain the current level of NTSC service in the large cities. During the transition period, the SFN approach is only required in places where there would not otherwise be enough channels to accommodate all of those intending to implement whatever digital service the Commission authorizes. This is likely to be only the large cities.[8] As the NTSC turn-off date approaches, a schedule can be made for the conversion to SFNs in other locations.

The SFN concept works for all radio transmissions, not only TV. Some services already are using cellular transmission for reasons other than SE. A good argument can be made that all radio transmission, at least in densely populated areas, should eventually shift to cellular schemes. As this process proceeds, the provision of common cellular transmis-

[8] Of course, if the SFN approach is to be used anywhere, a modulation method that can cope with the resulting multipath is required from the beginning.

sion sites will make a lot of sense. Leasing or buying property or sites, erecting the required facilities, and providing on-going service will prove to be much cheaper when all services use the same sites. The business of providing these facilities will be profitable, and it will permit many TV broadcasters, the overwhelming bulk of whose activities have nothing to do with physical transmission facilities even now, to get out of this business once and for all.

If such a service materializes, then the decision to go to a SFN becomes much easier to make. Less capital expense is involved, and it is not necessary for the broadcaster to learn the technologies required for SFN implementation.

5. Conclusions

In this submission, I have discussed the factors that influence the efficient use of spectrum in TV broadcasting. While the Grand Alliance system excels in compression, which depends on source coding, it does not achieve the best possible results in channel coding, which is of equal importance to spectrum efficiency. After the transition to a totally new system, and with the appropriate technology and regulations, it would be possible to reduce the allocation of channels for the over-the-air TV service from 67 to 20, while at the same time making it possible to provide 20 different programs to viewers in every part of the country. If these goals are considered worthy, then I suggest that the Commission do the following:

□ **Consider using single-frequency networks for digital television, at least in large cities.**

□ **Adopt a channel-coding and modulation method that can deal with the heavy multipath encountered in SFNs, without the use of high-performance directional antennas.**

□ **Mandate receiver selectivity adequate to eliminate current taboos other than adjacent-channel performance.**

□ **If the single-transmitter scheme is retained, then require all transmitting antennas in each city to be located at the same site so that adjacent channels can be used in the same city.**

Another difficulty with currently proposed plans is that all receivers must incorporate a complete decoder, thus adding unnecessary cost to small-screen sets. If the support of less-expensive receivers for less-demanding applications is deemed an important attribute of the new system, then the following can be done:

□ **Adopt a multiresolution approach in which the source coder produces a basic data stream plus two or more enhancement streams, and in which the channel coder packages this data so that the number of streams recovered depends on the signal quality at the particular receiver.**

This approach, when used in the single-transmitter scheme, also raises the SE by raising the image quality at close-in points and extending coverage at far-out points.

Appendix

Attached are three papers relevant to these comments:

1. W.F.Schreiber. "Advanced Television Systems for Terrestrial Broadcasting: Some Problems and Some Proposed Solutions," Proc. IEEE, 83, 6, June 1995, pp 958-981.

2. S.J.Wee et al, "A Scalable Source Coder for a Hybrid HDTV Terrestrial Transmission System," Proc. IEEE Intl. Conf. on Image Processing, November, 1994.

3. M.O.Polley et al, "Hybrid Channel Coding for Multiresolution HDTV Terrestrial Broadcasting," Proc. IEEE Intl. Conf. on Image Processing, November, 1994.

The first paper discusses a number of problems in terrestrial broadcasting of new television systems. It deals extensively with the question of spectrum efficiency and provides a technical background for these Comments.

The second and third papers describe the ATV system that has been simulated by my students and myself at MIT, the second dealing primarily with multiresolution source coding and the third with channel coding and modulation. They explain in some detail the operation of a system that can cope with single-frequency networks and with the analog channel impairments inherent in all terrestrial broadcasting.

It should be emphasized that no claim is made that this system is the best possible system for its purpose. The amount of resources that have been put into its development is far too small for that. However, it does serve as an existence proof that a system with much better spectrum efficiency than now planned is possible, so that, if implemented, the total amount of spectrum that would need to be allocated for the TV service would be substantially smaller than by any other currently proposed method. In addition, the multiresolution character of the system would support the design of less expensive receivers for less demanding applications.

Advanced Television Systems for Terrestrial Broadcasting: Some Problems and Some Proposed Solutions

WILLIAM F. SCHREIBER, FELLOW, IEEE

Invited Paper

The first part of this paper discusses the requirements that must be met by a new television broadcasting system to maximize its acceptability to the various stakeholders, including broadcasters, equipment manufacturers, program producers, regulatory authorities, and viewers. The most important performance factors are efficient use of over-the-air spectrum, coverage versus quality, cost, interoperability, and the existence of a practical transition scenario. It is concluded that all receivers need not have the same performance, and that low-cost receivers must be available for noncritical locations in the home. If this variation in price and performance is made possible by appropriate system design, then interoperability is facilitated and nondisruptive improvement over time is made possible, as desired by the Federal Communications Commission.

In the second part of the paper, techniques that may permit meeting these requirements are discussed. These include joint multiresolution source and channel coding, multicarrier modulation, and hybrid analog/digital coding and transmission. The analog transform coefficients are subjected to spread-spectrum processing, and coded orthogonal frequency-division multiplex (COFDM) is applied to the complex hybrid symbols to be transmitted through the channel. Various methods of equalization and of improving noise, interference, and multipath rejection are compared. Finally, an example is given of a system that meets the various requirements by making use of a number of the techniques discussed. The system provides extended coverage, albeit at lower quality than currently proposed all-digital systems, and equal or higher quality than such systems in much of their service area. It also features self-optimization at each receiver, depending on signal quality and receiver characteristics, and facilitates the design of receivers of lower cost and performance for less-critical applications.

I. INTRODUCTION

Since the proposal by General Instrument Corporation (GI) in 1990 for all-digital terrestrial broadcasting of high-definition television (HDTV), remarkable enthusiasm has developed in many quarters for what is, in reality, a truly radical departure from current practice. Digital technology, of course, had been widely accepted in many fields, including television post-production and video recording. Digital compression had been the subject of an international standardization process for several years under the aegis of JPEG and MPEG. The most notable features of the GI proposal were the degree of compression employed and the use of digital transmission technology. All of the earlier HDTV proposals, without exception, had made use of digital signal processing at encoder and decoder and had used some degree of digital compression. None, however, had used digital transmission. That technique, to the best of the author's knowledge, is currently employed in no terrestrial broadcasting system except for JTIDS, a US military system based on spread spectrum. The main applications of digital transmission are currently in wired point-to-point systems and in satellite communications. In those media, channel impairments are much less severe and receiver CNR[1] is much more uniform than found in terrestrial broadcasting. There, noise, interference, and multipath are particularly troublesome, and CNR varies enormously over the population of receivers.

For these and other reasons, many in the TV industry had thought that all-digital systems were very far in the future. Digital proposals had often been viewed as roundabout efforts to delay HDTV. Likewise, it had been the generally held (but incorrect) view that *any* amount of compression would be unacceptable because of loss of quality.

This being the case, it is natural to wonder what was the primary motivation for using digital transmission. A number of reasons were often given—better utilization of channel capacity, suppression of multipath effects, and higher resistance to noise and interference. Among those in the computer community who have been pressing for easy interoperability between the TV broadcasting format and

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The author is with The Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139 USA.

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[1] In this paper, CNR is used for the signal-to-noise ratio at the receiver terminals, and SNR is used when referring to the recovered video.

formats useful for displaying video on computer screens, it is often averred that digital transmission enhances interoperability. *All of these reasons are fallacious.*

As both system proponents and the Advisory Committee on Advanced Television Systems (ACATS)[2] personnel got more deeply into the details of the all-digital proposals, the first three alleged advantages were heard less and less. The interoperability argument, however, is still voiced. Since this issue is central to the subject matter of this paper, it is dealt with in some detail in Section III-A-3. The other matters are considered briefly in the Appendix. What we shall see is that digital transmission generally makes less efficient use of channel capacity than analog or hybrid analog/digital transmission. However, the very high compression ratio (50–80) achieved by the currently proposed HDTV systems reduces the data rate sufficiently so that coded HDTV signals can be transmitted at a gross data rate of 20–25 Mb/s, which, under the right conditions, can be transmitted in the usual 6-MHz channel. The real question is whether all-digital transmission is *required* in order to attain the required high levels of compression in the source coder. As we shall show later, hybrid transmission also permits effective compression.

In the earlier American TV standardization processes (1941 and 1953), a vigorous consumer-electronics industry spearheaded by RCA did the development work and the Federal Communications Commission (FCC) adopted, for the most part, the transmission format recommended by the industry. However, by the time the formal HDTV standards-setting process started in 1987, the US consumer-electronics industry had been decimated and proposals for federal funding were subsequently rejected. Thus the various development projects have been grossly underfunded and all competitors have worked under unrealistically short time schedules.[3] As a result, even though the development work has been of remarkably high quality, many issues were not given sufficient study. In particular, not enough attention was directed toward the characteristics that an entirely new TV system ought to have. Equally important, very little attention was given to coding methods for the terrestrial channel until after GI made its proposal. To this date, work on channel coding in the US remains far behind that in Europe. These topics are the main subject of this paper.

When speaking of "currently proposed" HDTV systems, we are referring to the Grand Alliance (GA) scheme, [1] which is a melding of the four all-digital systems that were tested by the Advanced Television Test Center (ATTC). Many of the features of the "ideal" system discussed below are intended to deal specifically with aspects of the GA system that the author feels are questionable for terrestrial broadcasting.

This paper is primarily addressed to HDTV in the US. The situation in Europe is quite different, for a number of reasons. In Europe, as compared with the US, government entities play a much larger role, the domestic consumer-electronics industry is much stronger, cable is less widespread and evidently of higher technical quality, and satellite broadcasting is further advanced. Many fewer terrestrial channels are available to each viewer, and a considerable investment was made in HD-MAC, a failed system. There has been almost no controversy over interlace, as the path to digital broadcasting seems to have been laid out in the expectation of very few changes in the studio. Digital television of standard definition is the evident current intention of cable and satellite interests in the US. In Europe, this also seems to be the case. In both areas, those planning digital services are all saying something about eventually going to HDTV, but ensuring that the first digital receivers can still function seems not to be getting much attention.

Many of the issues addressed in this paper involve political or economic considerations as well as technical matters. Therefore, the analysis cannot be entirely objective, nor can it always be quantitative. New television systems can no more be designed completely on a quantitative basis than can automobiles. Qualitative analysis, for example on the question of the best use of spectrum, is the only way to deal with some very important matters. It should be clear from the context which statements in the paper are the author's opinion and which are based on quantitative analysis.

II. Problems of Television Broadcasting

A. Performance Factors in Terrestrial Broadcasting

On the reasonable assumption that good solutions are most likely to be found when the problems are most completely and accurately defined, we shall now set forth the desirable properties of an entirely new TV system. Note that this is a much more difficult task than that encountered in typical new product development. A TV system must not only produce profits for a company; it must serve the public interest for many years to come and it must be acceptable to the many stakeholders—broadcasters, program producers, equipment manufacturers, and the viewing public. In the case of HDTV, an even wider constituency has emerged with the increasing use of video in other fields such as the computer industry and military equipment, and the often-expressed desire for interoperability among the various applications.[4]

1) Spectrum Efficiency: Standing at the head of any list of desirable attributes of a terrestrial broadcasting system is the effective use of radio spectrum. A useful figure of

[2] ACATS was appointed by the FCC in 1987 to conduct the inquiry that is leading to the promulgation of HDTV terrestrial broadcasting standards.

[3] It is not clear that the tight schedules have produced a quicker result. The reverse may be true, since the optimistic schedules have never been met. In addition, the intensity at which the work was carried out (one team worked on Christmas Day!) precluded much consideration of alternative technologies.

[4] This paper does not concern itself with issues, real as they are, such as the importance of electronic imaging to the economic security of the US, and the possibility that an entirely new development such as HDTV might be a way for the country to revive its moribund consumer electronics industry [2].

merit, which we shall call spectrum efficiency[5] in this paper, is defined as the number of different programs of a certain technical picture and sound quality that are made available to each viewer per unit of allocated spectrum. This measure depends both on the quality that can be delivered with a fixed bandwidth per program and the number of different programs that can be delivered within the overall spectrum allocation. These properties are associated with source coding and channel coding, respectively. It is obvious that source coding is concerned with data compression, while channel coding is concerned with interference performance. The two are of equal value and importance. They are further discussed in Section II-B.

The overwhelming significance of the efficient use of spectrum arises from the fact that there is considerably more demand than supply. The FCC, required by the Communications Act to regulate in the "public interest, convenience, and necessity," must constantly adjudicate among the claims of various parties for spectrum assignments. As mobile applications have become much more common, this has become an increasingly difficult job. Television is at the root of the problem since it has more than 400 MHz of the most easily used spectrum. A highly desirable outcome of the HDTV standard-setting process would be to maintain or even increase the present level of service while substantially decreasing the total allocated bandwidth.

2) Coverage versus Quality: Commercial broadcasters, who derive their income from advertising, live or die according to their coverage, since they get paid on a per-viewer basis. The main way in which they compete with each other is by means of program popularity, but they must reach the viewer in order to compete. They are therefore most reluctant to accept any new system that significantly reduces coverage. Unfortunately, coverage must be traded off against technical quality, since the latter depends on the information rate to the receiver. The theoretically maximum information rate per unit bandwidth depends primarily on the signal-to-noise and signal-to-interference ratios at the receiver. The higher the CNR required for a given quality, the smaller the coverage, whether limited by noise or by interference. This tradeoff is also affected by the compression achieved in the source coder, as compression decreases the information rate needed for a given quality. Thus the fundamental question in coverage is whether sufficient compression can be achieved in the source coder to maintain coverage with a given quality while at the same time permitting a practical transition scenario from today's National Television Systems Committee (NTSC)[6] broadcasting to whatever will replace it. Because it has such low spectrum efficiency, almost everyone now agrees, albeit reluctantly, that NTSC must eventually be replaced.

a) Noise performance: The theoretical (Shannon) capacity, in bits per second, that is available to a receiver connected to an analog channel is proportional to the product of bandwidth and (1+CNR) in dB. When the input is a multilevel signal, so as to effect digital transmission in such a channel, the error-free recovered data rate is usually less than the Shannon rate for a number of reasons. Clearly, if the level-spacing is too large relative to the RMS noise, the input must have a data rate less than the Shannon rate. No kind of postprocessing can cure this problem. If the level spacing is fine enough so as not to reduce the input data rate excessively, error correction must be used.[7] Very effective error-correction methods, using trellis coding and Viterbi decoding, are now available. Even so, the net recovered data rate, R, is reduced by any remaining errors according to the relationship

$$R = R_o - H(e)$$

where R_o is the error-free transmission rate, i.e., the maximum possible entropy of such a multilevel input signal, and $H(e)$ is the equivocation, or entropy of the error distribution. Essentially, the data throughput rate is reduced by the amount of information required to identify (and correct) the errors [3].

When high compression ratios are achieved in the source coder, the recovered information is usually more readily damaged by transmission errors. Thus, error correction must be used. Shannon proved that codes exist that permit transmission as close to the theoretical rate as desired with as small a bit error rate (BER) as desired. This involves removing all of the redundancy from the transmitted signal. If we could do that, we would find that the signal was very fragile and that it took a long time to resynchronize after an error. High channel-coding efficiency also implies a large amount of delay and more expensive processing. In practice, it is unusual to achieve even 75% of the Shannon rate, even at the given threshold CNR. In broadcasting, most of the receivers have a higher CNR than that at threshold. At these sites, channel capacity is higher than the transmission rate and, therefore, the efficiency is lower.

Another characteristic of effective error-correction systems is a very sharp threshold. In a heavily coded system, less than a 1-dB change in CNR takes one from perfect reception to no reception at all. This so-called "cliff effect" is not entirely a bad thing. In order to minimize the no-man's land between two different stations on the same channel, a sharp threshold may be helpful. However, it also leads to performance that is very different in character near the boundary of service from what is achieved in analog transmission. The viewing public is used to pictures getting a little worse or a little better, but not disappearing completely, every time a truck goes by or the character of

[5] Unfortunately, this term is sometimes used with the more limited meaning of transmission rate in bits per cycle of bandwidth.

[6] NTSC, an industry group, promulgated standards for television broadcasting in the US in 1941 and 1953. The proposed standards were adopted with little change by the FCC.

[7] Although this discussion is in terms of quantization of single samples, it applies equally to more sophisticated schemes in which a long train of samples is coded together as a single message. The selection of a finite number of such possible messages from the infinite number that is associated with unquantized analog samples is equivalent, for this argument, to the quantization mentioned above. The decision at the receiver as to which message was transmitted on the basis of minimum distance in multidimensional signal space is equivalent to the selection, at the receiver, of the nearest level to the received sample value.

an interfering signal changes. Although these considerations are very important, they are not amenable to quantitative analysis.

b) Co-channel interference: While noise can be effectively suppressed by raising the signal power, this increases interference to nearby stations. If all stations raised their power by the same amount, noise sensitivity would go down, but the interference situation would be unchanged. In the transition scenario in which HDTV and NTSC are to coexist for 15 years, the HDTV stations will be limited in power so as not to reduce the coverage of NTSC stations significantly. As a result, they may be noise-limited in portions of their intended coverage areas where there is no potential interference from an existing NTSC station.

One of the main defects of NTSC is that all transmissions are highly correlated. This causes one picture to appear on top of another when there is interference.[8] For a given strength signal interfering with an analog video transmission, the least-perceptible effect is produced by signals that appear to be random noise. Wisely, this has been done in HDTV, where each signal appears to be random noise to other signals. This means that the required signal/interference ratio is virtually identical to the required signal/noise ratio.

c) Adjacent-channel interference: This is a different question from cochannel interference, since there seems to be no reason why we cannot use adjacent channels in the same area provided that receivers have good-enough selectivity. The problem arises when a viewer tries to receive a distant station when there is a nearby station in an adjacent channel. This is not only a question of selectivity, it is also a question of out-of-band radiation by the nearby station. There is a limit to how much attenuation can be provided by filters at the transmitter without unduly distorting the in-band signal.

This problem can be solved either by placing all transmitters in any one city at the same location,[9] or by making use of modulation methods that inherently restrict out-of-band radiation, as in OFDM. On cable, where all signals are of the same amplitude, typical receivers have no trouble discriminating against signals in the adjacent channel.

d) Multipath: The final obstacle to effective use of the terrestrial transmission channel is multipath, i.e., the reception of a number of signals that have traveled over different paths from transmitting antenna to receiving antenna and therefore arrive displaced in time. In analog systems this causes the familiar ghosts, while in digital systems, it raises the error rate. The effect in digital systems is so strong that multipath must be essentially eliminated in order to permit any useful transmission at all. Elimination of ghosts in analog systems greatly improves picture quality, but the presence of ghosts does not generally make the service completely unusable.

Multipath is a linear distortion, so the effect is to produce a nonuniform frequency response across the channel, exactly as if an unwanted linear filter were processing the transmitted signal. It therefore can be corrected, within limits, by the use of the appropriate compensating filter, a process called linear equalization. First used in telephone circuits, the theory and practice of linear equalization are highly developed [4]. In the presence of noise, there are limits on what can be done. Large echoes cause deep notches in the frequency response, and correction by linear equalization may greatly increase the noise level. Noise in the received signal also makes determination of the parameters of the equalization filter slower and more difficult. For all these reasons, effective equalization requires a lot of computation. For example, in the GI system, one-third of the receiver signal-processing circuitry is used for this function [5].

3) Cost to the Stakeholders: In order for a new TV system to go on the air, it must be accepted by broadcasters, equipment manufacturers, and program producers. Once these difficult hurdles are surmounted, final success depends on acceptance by advertisers and viewers, who, in the end, will pay for the entire system. The different stakeholders have different needs [6], but near the top of everyone's list is cost.

a) Broadcasters: As mentioned above, broadcasters have little motivation to shift to HDTV except to help preserve audience share. If it appears that there is no way to stay in business while avoiding HDTV, then, of course, they will want to make the change. Their ability to do so depends very much on the availability and cost of the necessary equipment—cameras, VCR's, special effects, and other studio equipment, transmitters, etc. Virtually all this equipment must be newly purchased. Of course, the move to HDTV can be accomplished in stages, such as first simply passing through signals received from the network, then using taped or filmed productions, and finally, originating entire programs. This process will be quite expensive and will not be accomplished overnight.

During the transition period, the NTSC equipment must be kept running, as the market for HDTV broadcasting will grow slowly and simulcasting has been mandated by the FCC. Thus broadcasters face extra expenses for a long time to come. One problem they probably will not face is a shortage of program material. Virtually everything produced on film for NTSC is good enough for HDTV. This takes care of much of prime-time programming. Sports programs are another sure bet, as the wide screen and higher definition will add perceptibly to the visual effect. Of course, outside broadcasting equipment is needed for this function. Many current daytime programs really do not need HDTV and may well be aired in standard definition for many years to come, perhaps by using compression technology to fit several programs into one 6-MHz channel.

b) Equipment manufacturers: The Japanese companies that designed studio equipment to go with the NHK system

[8] If one were perversely designing an analog video system to achieve maximum interference, one would make all the transmitting systems scan in synchronism, like NTSC and PAL.

[9] Evidently, at the time that channel allocations were originally made, there was not enough pressure on spectrum so as to mandate colocation of all transmitters within each city. With the reallocation opportunity provided by the shift to HDTV, this matter can be revisited.

are no doubt looking forward with great anticipation to the time when HDTV becomes a commercial reality so that they can begin to recoup their already very substantial investment. To some extent, the European manufacturers who did the same for HD-MAC will also be happy to make equipment for any system. Modification of their designs to accommodate a different coding system will cost much less than has already been spent on the design of cameras, monitors, VCR's, etc.

The situation with respect to receiver manufacturing is somewhat different, as the initial investment is much larger and the profit margins are much smaller than for professional equipment. Of course, the receiver manufacturers are also looking forward to HDTV broadcasting as opening a new market to them. In all likelihood, they will have little trouble finding the money required to enter the field, but they will be a good deal more cautious about committing to large-scale production until the level of uncertainty is reduced. Here price is the main factor, along with programming, that will determine the speed of penetration and therefore the possibility of making profits. Many observers think that an initial price of \$3000–4000 would not be excessive. Both monochrome and color sets cost about that at today's prices when they were first introduced. The real question is whether HDTV receivers of, say, 35-in size, can be sold at that price, without losing money, within a year or two of introduction.

In NTSC sets, the cost of signal processing is negligible compared to the cost of display, cabinet, etc. That will not be the case with HDTV, as the processing power required far exceeds that found in today's most powerful personal computers. While there are many who argue that complexity is no longer a cost issue, the chips required for a system based on MPEG are exceedingly complicated. Pentium chips, for example, cost about \$500[10] and they have much too small a capacity for real-time MPEG decoding. If HDTV is very successful, the volume should eventually exceed that of PC's. This is very much a "chicken and egg" problem in which it is hard to predict just what will happen.

c) Program producers: Like professional equipment manufacturers, program producers will probably be adequately motivated to get into HDTV as they see the market developing. Naturally, they will be influenced by cost considerations. In the case of 1125/60, which is already being used to some extent (although, except in Japan, the product must be converted to NTSC or PAL for broadcast), it is thought that concessional prices were offered by the equipment manufacturers in many cases.

d) Advertisers: Advertisers will certainly use any medium that brings them an audience, and will certainly not use any medium that does not. In the case of simulcasting, the total audience presumably will be only slightly more than would have been obtained with NTSC alone, so the total payment will only be marginally higher than for NTSC. It is conceivable that it will be found that certain kinds of advertising are more effective in high definition. In that case, advertisers will be more interested. In any event, it appears quite doubtful that advertising receipts can be counted on to pay for the transition to HDTV. When color was added to NTSC, RCA supported the new format to the extent of about \$3 billion at today's prices. Who will provide the required investment this time is not clear.

e) Viewers: As mentioned above, \$3000 would be an acceptable price for a large HDTV receiver, judging by earlier introductions of new systems such as NTSC color. In estimating the speed of market penetration, it should be recalled that it took 10 years to reach 1% penetration in that case, which was similar to the proposed transition to HDTV, since the same programs were seen in both formats. On the other hand, the receiver market today is very different from that in the 1950's. At that time, there were many domestic manufacturers, and many of these were making good profits. Intense competition has taken much of the profit out of the industry and caused most domestic manufacturers to go out of business.[11] It is therefore conceivable that it will prove impossible to create a mass market with receivers that cost so much.

There is another factor, however, which goes beyond price, and that is the relative attractiveness of the new and old formats in themselves, regardless of programs, which will be the same. Our own audience tests at MIT clearly showed that the relative preference for HDTV over NTSC, when both were shown with the same programs at studio quality, was small [7]. It seems obvious that the perceived difference would be much smaller than that between monochrome and color. However, we also found, indirectly, that there was a large perceived difference between studio quality, as used in the tests, and average quality in the home.

The decision to use digital transmission, about which the author has some serious reservations, does have a benefit in this case. With digital transmission, it is not possible to receive pictures that are seriously degraded by channel impairments.[12] *With NTSC, badly degraded pictures in the home are the norm.* Provided that adequate coverage and reliability are achieved with the all-digital system in the presence of the usual analog channel impairments, and provided that compression itself does not produce serious impairments for a significant proportion of subjects, for the first time viewers will be seeing studio-quality images in the home. This is likely to be perceived as a substantially larger benefit than the higher definition. While it is a truism that viewers care much more about program content than about technical image quality, in this case they will see a

[10] On August 1, 1994, Intel reduced the price of 66-MHz Pentium chips from \$750 to \$525, in 1000 lots. Of course, TV decoders are unlikely to use completely programmable decoders in the forseeable future. This example is given only to show that very complex chips are not soon likely to be cheap even in very large quantities.

[11] The only large American owned consumer-electronics company at present is Zenith, and that company does all of its manufacturing in Mexico. The largest manufacturers in the US are North American Philips and Thomson. The latter, owned by the French government, bought the consumer-electronics divisions of GE and RCA.

[12] Whether or not this is a benefit depends on how the overall system is designed. Extended coverage would be highly desirable even if there were some reduction in picture quality.

side-by-side difference in the store that may turn out to be important.

There are some who think that the 16:9 aspect ratio will be an important aspect of the appeal of digital TV. Of course, wide aspect ratio is also possible in analog systems, such as PAL Plus. There seems to be no good evidence that the wide screen is very important by itself. My personal opinion, which is shared by many in the creative community, is that the best aspect ratio is the one that was used to make the original production; e.g., portraits should be done in "portrait mode" and landscapes should be rendered in "landscape mode." In the focus groups used in the MIT audience-testing program, no evidence at all emerged that demonstrated that the wide screen, by itself, was a very important feature. The single parameter of the display that overshadowed all others, including sharpness, was image size.

4) An Acceptable Transition Scenario: In 1988, Zenith proposed a noncompatible HDTV transmission system that would use the taboo channels at low power, together with simultaneous transmission of the same programs on NTSC in current channels. Primarily on the basis of this proposal, the FCC decided to use simulcasting rather than a compatible signal format to serve existing receivers for a certain period. Broadcasters, who previously had been nearly unanimous in preferring a backward-compatible HDTV system, reluctantly went along. Ironically, Zenith's estimate of the adequate power level of the new stations was very far below what was later shown to be necessary. In addition, the source-coding method proposed at that time did not produce sufficiently good picture quality and was later abandoned. Nevertheless, the FCC stayed with its simulcasting decision, and eventually systems were developed that come close to meeting its requirements.

In one way, simulcasting solves the "chicken and egg" problem of noncompatible systems, in that the existing audience sees all the new programs, although not in HDTV. On the other hand, it removes much of the incentive to buy new receivers, since the old receiver permits viewing the new programs, just as if a receiver-compatible system had been used. It remains to be seen whether improvement in technical picture quality, by itself, will motivate consumers sufficiently to buy what are likely to be rather expensive new receivers. The alternative—attracting viewers to the new service by providing very desirable programs that cannot be seen any other way—was apparently rejected by everyone concerned as much too risky. My own opinion was that this course might have proven successful if a smaller and less price-conscious market, such as hotel television, had been tried rather than going immediately for the mass market.

In any event, the general idea of using simulcasting during the transition period is certainly feasible. That was the approach used in France and the UK when PAL was introduced in 1967. Old receivers were served for about 20 years, although not with all of the same programs made available on the new service. No one is immediately disadvantaged by simulcasting, but it does leave unanswered the question of how rapidly the public will make the shift to new receivers. If the FCC can stick to its intention of shutting down NTSC after 15 years, then, as that time approached, we would expect more sales of HDTV sets. One can expect the marketing of set-top converters from HDTV to NTSC to thrive, especially as, at least for some time, NTSC receivers will continue to be used with videotapes. Not only is 15 years a long time to wait for a market to develop, there remains some doubt whether Congress would allow NTSC ever to be abandoned if the public were strongly opposed.

A complete transition would mean discarding all NTSC equipment and making obsolete all existing receivers. An absolute necessity for this to be acceptable would be the availability of small inexpensive "HDTV" receivers, some portable, to serve the same functions that such receivers now serve. We do not want or need a theatrical experience while watching the morning news during breakfast, nor do the children need it for much of what they are now watching. We certainly do not want to pay very high prices for small receivers.

The main problem in making inexpensive sets to receive the HDTV signal is that, with existing American proposals, full decoding to baseband is required. The high-resolution image thus produced must then be processed to get the lower-resolution signal for the cheaper display. The need for a full decoder may well increase the cost of each set by several hundred dollars, and the selling price by even more. It would be better to have a coding system in which complete decoding were not required in low-performance sets. Even better would be a system with at least three levels of quality, with the cost of the decoder ranging from very low for the cheapest and smallest sets to substantially more for the full-quality receivers. This may well be feasible, but it is not part of the Grand Alliance proposal.

B. Regulatory Issues

Many aspects of TV system design cannot be settled by comparative testing; they must be decided on the basis of our preferences and the exigencies of the spectrum allocation problem. For example, coverage can be measured, but the aspect ratio must be decided upon on the basis of our preferences. The ability to function in the presence of a given degree of multipath can be tested, but whether we should deliver the same picture quality to everyone regardless of the distance from the transmitter is a policy issue. The amount of spectrum to be allocated to TV and the amount of service to be provided are basically political decisions.

1) What Kind of a TV System Do We Want? After about a half century of experience with television in the US, we have a good idea of its potential benefits and possibilities. Now that the time has arrived to have a new system, we have a rare opportunity to shape the medium in accordance with our collective views. Decisions on the overall nature of the service cannot be left entirely to the marketplace, since an enormous investment must be made before the